INVESTIGATION OF THE FLOW PHYSICS DRIVING STALL-SIDE FLUTTER IN ADVANCED FORWARD SWEPT FAN DESIGNS

Albert J. Sanders, Jong S. Liu, & Josef Panovsky
Honeywell Engines, Systems & Services
Phoenix, Arizona

Milind A. Bakhle & Rakesh Srivastava
University of Toledo
Toledo, Ohio

George Stefko
NASA Glenn Research Center
Cleveland, Ohio

Contact Author: Al Sanders
Honeywell Engines, Systems & Services
111 South 34th Street
MS 301-134
Phoenix, AZ 85034
Ph: 602-231-2156
Fx: 602-231-3087
Em: Al.Sanders@Honeywell.com

INTRODUCTION

Flutter-free operation of advanced transonic fan designs continues to be a challenging task for the designers of aircraft engines. In order to meet the demands of increased performance and lighter weight, these modern fan designs usually feature low-aspect ratio shroudless rotor blade designs that make the task of achieving adequate flutter margin even more challenging for the aeroelastician. This is especially true for advanced forward swept designs that encompass an entirely new design space compared to previous experience. Fortunately, advances in unsteady computational fluid dynamic (CFD) techniques over the past decade now provide an analysis capability that can be used to quantitatively assess the aeroelastic characteristics of these next generation fans during the design cycle.

For aeroelastic applications, Mississippi State University and NASA Glenn Research Center have developed the CFD code TURBO-AE. This code is a time-accurate three-dimensional Euler/Navier-Stokes unsteady flow solver developed for axial-flow turbomachinery that can model multiple blade rows undergoing harmonic oscillations with arbitrary interblade phase angles, i.e., nodal diameter patterns. Details of the code can be found in Chen et al. (1993, 1994), Bakhle et al. (1997, 1998), and Srivastava et al. (1999). To assess aeroelastic stability, the work-per-cycle from TURBO-AE is converted to the critical damping ratio since this value is more physically meaningful, with both the unsteady normal pressure and viscous shear forces included in the work-per-cycle calculation. If the total damping (aerodynamic plus mechanical) is negative, then the blade is unstable since it extracts energy from the flow field over the vibration cycle.

TURBO-AE is an integral part of an aeroelastic design system being developed at Honeywell Engines, Systems & Services for flutter and forced response predictions, with test cases from development rig and engine tests being used to validate its predictive capability. A recent experimental program (Sanders et al., 2002) was aimed at providing the necessary unsteady aerodynamic and vibratory response data needed to validate TURBO-AE for fan flutter predictions. A comparison of numerical TURBO-AE simulations with the benchmark flutter data is given in Sanders et al. (2003), with the data used to guide the validation of the code and define best practices for performing accurate unsteady simulations. The agreement between the analyses and the predictions was quite remarkable, demonstrating the ability of the analysis to accurately model the unsteady flow processes driving stall-side flutter.

FIRST GENERATION FORWARD SWEPT FAN

A first generation forward swept shroudless fan, referred to as the Quiet High Speed Fan I (QHSF I), was designed by Honeywell in the mid-1990s as part of a noise reduction initiative sponsored by NASA. Even though the fan did achieve significant noise reduction over the baseline aft swept fan, a severe stall-side flutter problem prevented the fan from entering production. Development rig testing at Honeywell revealed that the flutter zone extended across the entire operating range, with the flutter boundary even extending below the sea level static operating line at part-speed operating conditions. Similar testing over a much narrower operating range on a different rig at NASA revealed similar flutter characteristics, with the tested flutter boundaries for both rigs depicted in Figure 1. Analysis of the strain gage data indicated that flutter occurred in the first bending mode as a 2 nodal diameter forward traveling wave.

Panovsky et al. (2002) utilized TURBO to investigate the flutter characteristics of this fan at 75%, 85% and 100% corrected speed. Both viscous and inviscid flutter analyses were performed, with the aerodynamic damping predictions at 85% corrected speed shown in Figure 2. This figure shows the variation of aerodynamic damping with nodal diameter for a peak efficiency (PE) and a near stall (NS) operating condition close to the measured flutter boundary. The overall range of damping for both operating conditions varies dramatically with nodal diameter, with the +2 nodal diameter predicted to be the least stable in the near stall viscous simulation, which is consistent with the strain gage test data. The inviscid predictions were found to be in remarkably good agreement with the viscous analyses for both operating conditions, indicating that the flow physics driving stall-side flutter for this fan were primarily inviscid in nature.

In order to predict the flutter boundary, the aerodynamic damping predictions as a function of mass flow were linearly extrapolated to define the mass flow corresponding to zero damping using the peak efficiency and near stall simulations. The viscous flutter boundary prediction using this extrapolation technique at 75%, 85%, and 100% corrected speed agreed quite well with the tested boundary as depicted in Figure 3. Similar work by Sanders et al. (2003) on an aft swept fan has also shown that the aerodynamic damping varies nearly linearly with flow and that accurate flutter boundary predictions are obtained using this extrapolation technique. Sensitivity studies were also performed and it was found that variations in blade geometry due to speed changes, changes in the inlet and exit profiles, and tip clearance all had very small effects on the aerodynamic damping predictions (Panovsky et al., 2002).

SECOND GENERATION FORWARD SWEPT FAN

A second generation forward swept fan design (QHSF II) has recently been performed which is the major focus of the present paper. This fan design is also derived from an aft swept baseline rotor design which is different than that utilized for QHSF I. This baseline design has undergone extensive development and certification testing without encountering any flutter problems. Whereas limited unsteady CFD analyses were performed during the design of QHSF I due to the lack of validated analytical tools, significant progress has been made since that time to enable fully unsteady CFD based flutter analyses to be utilized for the design of QHSF II. Since forward sweep effects were thought to be the primary cause of the QHSF I flutter problem, the impact of forward sweep on the flutter characteristics of the QHSF II fan were investigated first during the preliminary design phase.

A design of experiments (DOE) was conducted to quantify the effects of forward sweep on the flutter characteristics of the new baseline design from which QHSF II is derived. Recall that the TURBO-AE analyses of QHSF I indicated that the primary drivers for stall-side flutter were inviscid in nature. Inviscid analyses were thus used for this preliminary DOE since they require only 2-5% of the computational time required for the viscous analyses and capture the primary drivers for flutter. A total of 25 rotor blade designs were included in the DOE, with the baseline aft-swept fan blade re-stacked to generate new rotor designs with various degrees of forward sweep. Figure 4 displays the airfoil section stacking distributions used for the DOE, with specific cases shown for clarity. The blade span is displayed on the horizontal axis while the axial location of the stack axis is displayed on the vertical axis, with a positive XCG shift corresponding to forward sweep and a negative XCG shift to aft sweep. The range of sweep angles, both forward and aft, encompass the baseline aft swept design from which QHSF II is derived as well as QHSF I.

Inviscid TURBO-AE analyses were conducted at 89% speed for each of the 25 DOE cases, with the unsteady simulations performed for peak efficiency and near stall operating points at nodal diameters of –2, 0, 2, 4, 6, and 11. Surprisingly, forward sweep was found to have a very small effect on the flutter characteristics of the fan. In fact, the small differences in flutter predictions can be traced back to changes in the airfoil mode shape (twist-to-flex ratio) and reduced frequency due to re-stacking the sections. As will be shown later, the single most important parameter affecting the flutter characteristics of the design were related to the blade vibratory mode shape, and that the forward sweep was not the reason why QHSF I experienced stall-side flutter.

To quantify the effect of mode shape on the flutter characteristics of the fan, several candidate fan designs were analyzed with varying degrees of twist-to-flex ratio as depicted in Figure 5. Notice that range of mode shapes analyzed spans the stable design space of the baseline design to the unstable design space of QHSF I. For each of these candidate designs, viscous flutter simulations were performed over a range of nodal diameters for several speedlines. The viscous flutter predictions for the least stable nodal diameter pattern for the three candidate fan designs are shown in Figure 6. Notice that the flutter predictions for QHSF I (Figure 2) and the initial go-forward design are very similar, with both designs predicted to have severe flutter problems near 70% corrected speed. As seen in Figure 5, both the QHSF I and initial go-forward designs have very similar mode shapes which explains the similar flutter characteristics. Similarly, decreasing the twist-to-flex ratio has a strong stabilizing effect on the flutter characteristics, with this behavior consistent with experience.

ADDITIONAL WORK

The above results demonstrate that mode shape has a significant effect on the flutter boundary predictions for the fan design. Additional work will be performed to investigate the effect of mode shape on the unsteady aerodynamics which drive flutter. This will include determining how the aerodynamic damping varies along the speedlines for each mode shape, how the mode shape affects the slope of the aerodynamic damping versus flow curves, an investigation to quantify the stabilizing effect of mechanical damping as a function of mode shape, etc. The result will be a more thorough and detailed description of how unsteady CFD based techniques can be used to mitigate flutter concerns in advanced fan designs.

REFERENCES

Bakhle, M. A., Srivastava, R., and Keith, T. G. Jr., 1998, "Aeroelastic Calculations Based on Three-Dimensional Euler Analysis," AIAA Paper No. 98-3295.

Bakhle, M. A., Srivastava, R., and Keith, T. G. Jr., 1997, "A 3D Euler/Navier-Stokes Aeroelastic Code for Propulsion Applications," AIAA Paper No. 97-2749.

Chen, J. P., Celestina, M., and Adamczyk, J. J., "A New Procedure for Simulating Unsteady Flows through Turbomachinery Blade Passages," ASME Paper No. 94-GT-151.

Chen, J. P. and Whitfield, D. L., "Navier-Stokes Calculations for the Unsteady Flowfield of Turbomachinery," AIAA Paper No. 93-0676.

Panovsky, J., Bakhle, M. A., and Srivastava, R., 2002, "Flutter Characteristics of a Forward-Swept Fan," Paper Presented at the 7th National Turbine Engine High Cycle Fatigue (HCF) Conference, Palm Beach Gardens, Florida, May 14-17.

Sanders, A. J., Hassan, K. K., and Rabe, D. C., 2003, "Experimental and Numerical Study of Stall Flutter in a Transonic Low-Aspect Ratio Fan Blisk," ASME Paper No. GT2003-38353.

Sanders, A. J., Rabe, D. C., and Fost, R., 2002, "An Experimental Investigation of Stall Flutter in an Advanced Design Low-Aspect Ratio Fan Blisk," Paper Presented at the 7th National Turbine Engine High Cycle Fatigue (HCF) Conference, Palm Beach Gardens, Florida, May 14-17.

Srivastava, R., Bakhle, M. A., and Keith, T. G. Jr., 1999, "Phase-Lagged Boundary Condition Methods for Aeroelastic Analysis of Turbomachines - A Comparative Study," ASME Paper No. 99-GT-19.

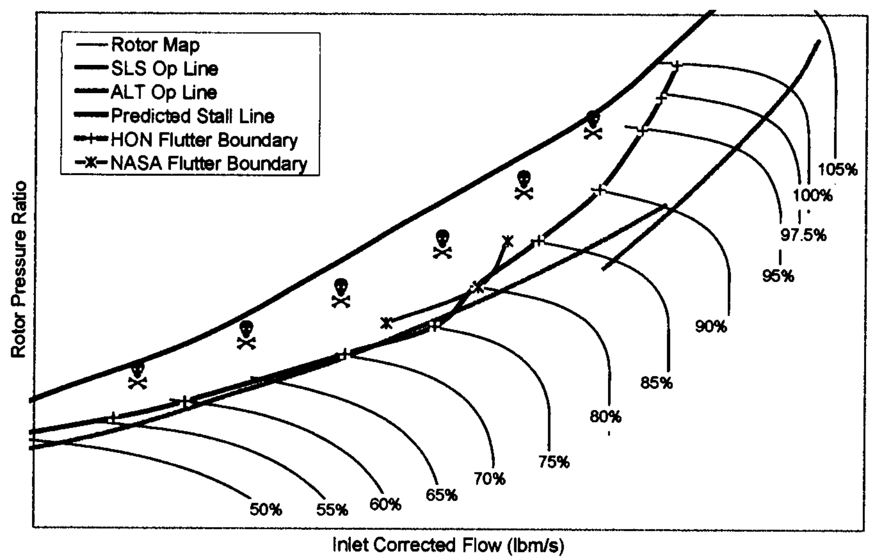

Figure 1. First Generation Forward Swept Fan Map with Flutter Boundary.

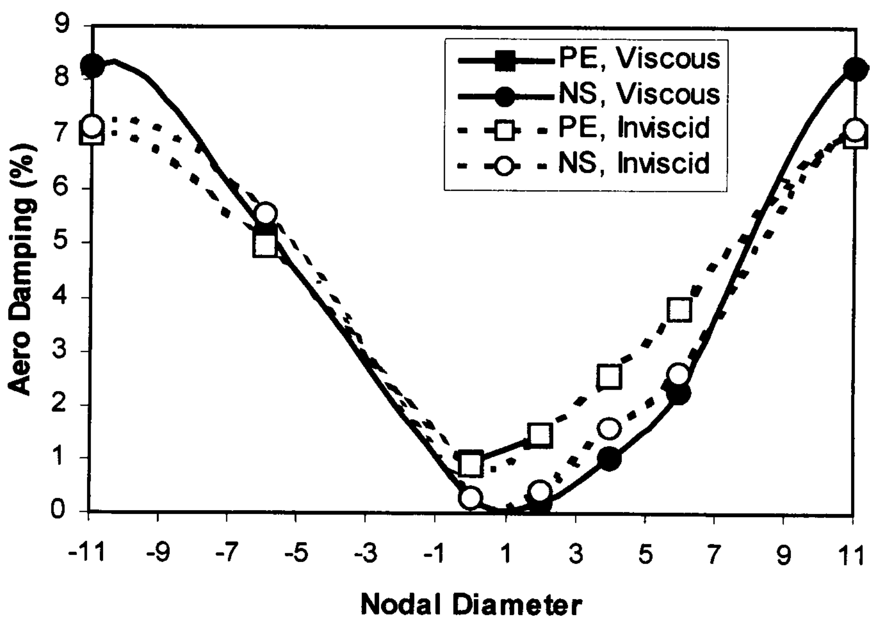

Figure 2. Aerodynamic Damping Predictions at 85% Corrected Speed.

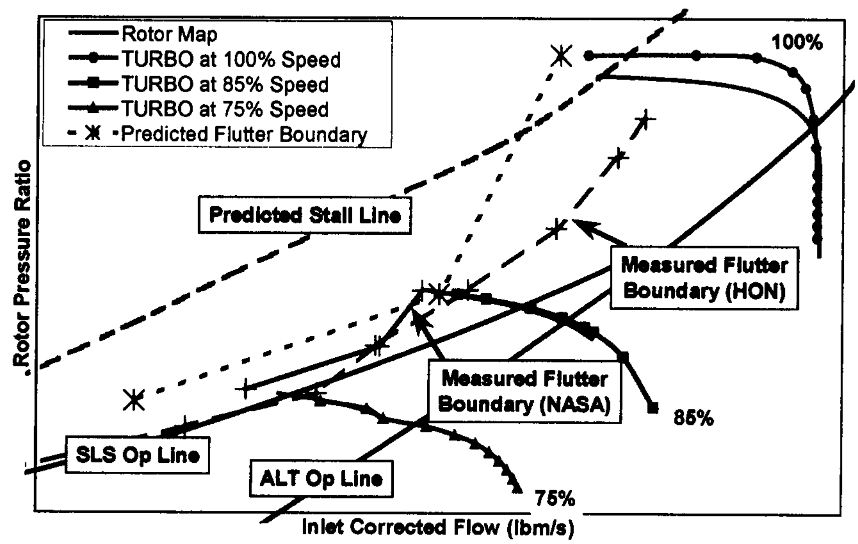

Figure 3. First Generation Forward Swept Fan Flutter Boundary Prediction.

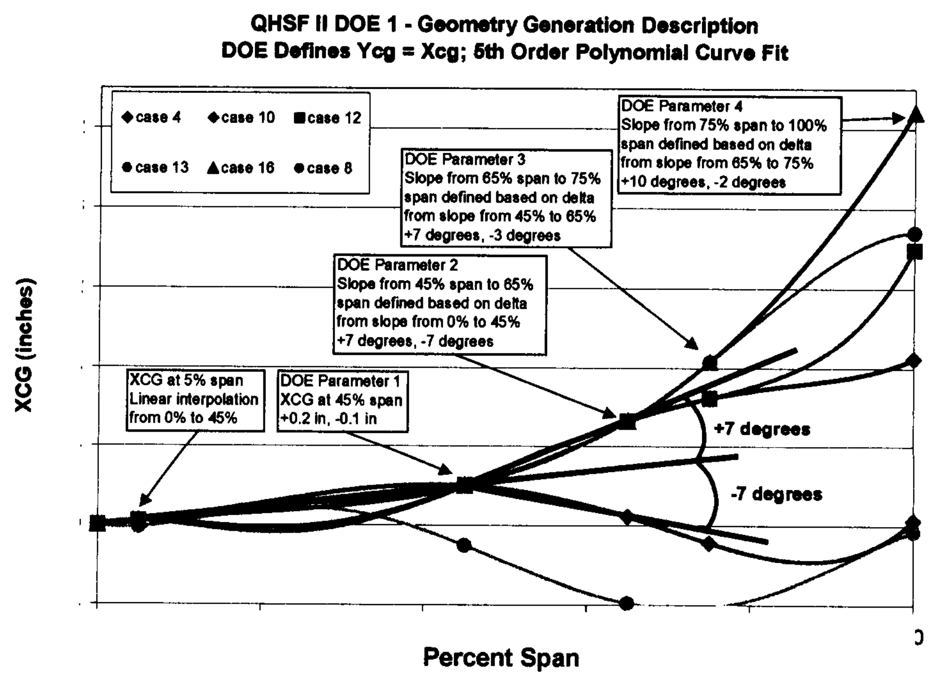

Figure 4. Rotor Stack Axes for QHSF II DOE.

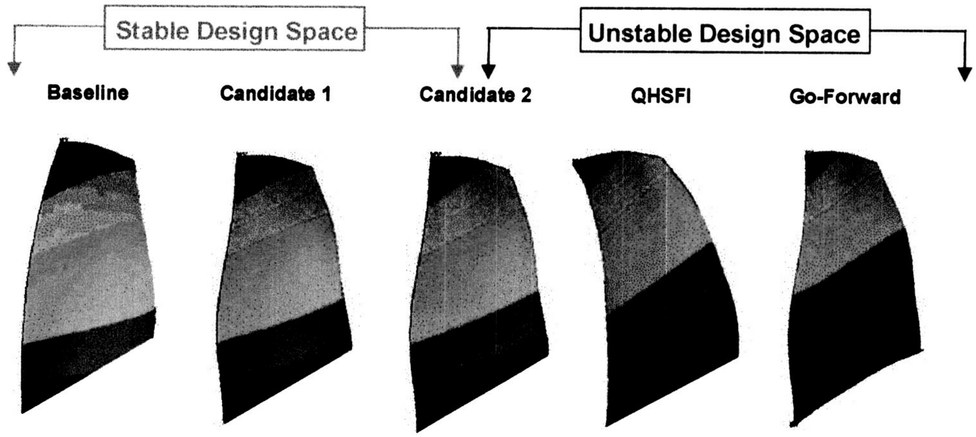

Figure 5. Mode Shape Tailoring to Mitigate Flutter Risk.

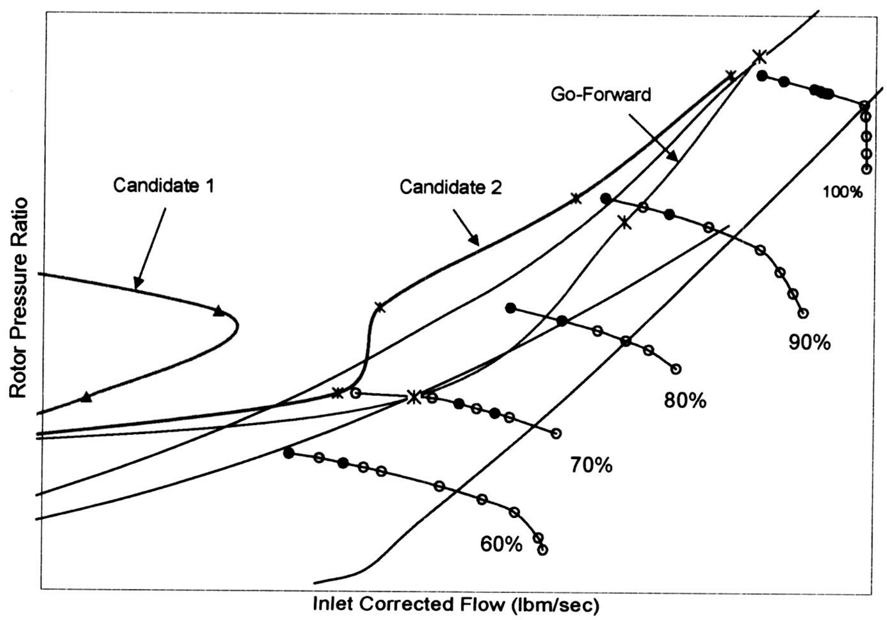

Figure 6. Flutter Boundary Predictions for Various Mode Shapes.